

**Lake Michigan Shoreline TMDL for *E. Coli* Bacteria**

**Modeling Framework Report**

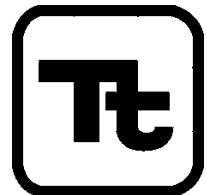
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## 1.0 INTRODUCTION

Lake Michigan has a total shoreline length of 1,638 miles and about 43 miles of shoreline lie within the state of Indiana (see Figure 1). The Indiana shore includes Indiana Dunes National Lakeshore as well as several other beaches that are used extensively by residents of Indiana and other Midwest states (see Figure 2). The shoreline is listed on the Indiana 303(d) list of impaired waters for failing to fully support its designated swimmable use due to *Escherichia coli* (*E. coli*) impairment (Table 1). The *E. coli* impairment was identified through data collected by the Indiana Department of Environmental Management (IDEM) and the Inter-Agency Technical Task Force on *E. coli* (Task Force) that showed violations of the water quality standard. *E. coli* is a bacterium that indicates the presence of human sewage and animal manure. It can enter water bodies through direct discharge from mammals and birds, from agricultural and storm runoff carrying mammal waste (manure), and from sewage leaked into the water. *E. coli* is also an indication of the possible presence of other disease causing organisms or pathogens. Violations of the water quality standard resulted in an average of more than 15 beach closures per year at the National Seashore and state park during the 1990 to 2000 period (Luther, 2001). These beach closures have been associated with adverse recreational and economic costs to the locality.

**Table 1. Listing information for Lake Michigan from the Indiana 1998 section 303(d) list.**

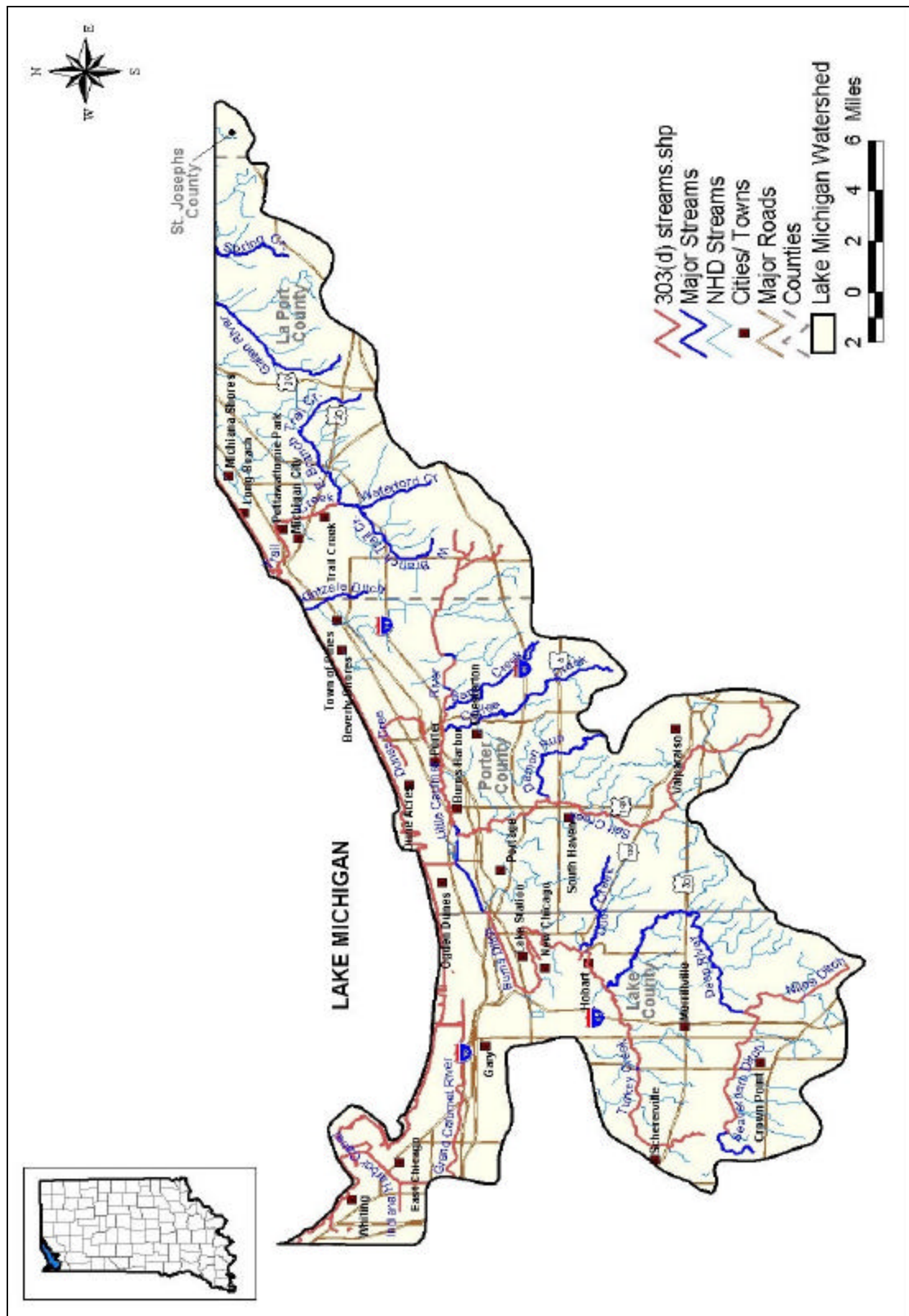
Waterbody	Designated Use	Support Status	Parameters of Concern
Lake Michigan	Aquatic Life Use	Full Support	--
	Swimmable	Partial Support	<i>E. coli</i>

The Clean Water Act (CWA) and U.S. Environmental Protection Agency (USEPA) regulations require that states develop Total Maximum Daily Loads (TMDLs) for all waters on the section 303(d) lists. A TMDL is the sum of the allowable amount of a single pollutant that a waterbody can receive from all contributing point and nonpoint sources and still support its designated uses. IDEM is in the process of developing *E. Coli* TMDLs for the Lake Michigan Shoreline and tributaries. The overall goals and objectives of the project are to:

- Further assess the water quality of the shoreline waters and identify key issues associated with the impairments and potential pollutant sources.
- Use the best available science to determine the maximum load of *E. Coli* that the shoreline waters can receive and still fully support all of its designated uses.
- Use the best available science to determine existing loads of *E. Coli*
- If existing loads exceed the maximum allowable load, determine the necessary load reduction.
- Identify feasible and cost-effective actions that can be taken to reduce loads.
- Inform and involve the public throughout the project to ensure that key concerns are addressed.
- Submit a final TMDL report to USEPA for review and approval.

Previous reports have described the data available to develop the TMDL (Tetra Tech, 2003a) and estimated the likely sources of *E. coli* (Tetra Tech, 2003b). The purposes of this report are to:

- Describe the modeling that will be done to identify the cause and effect relationship between the sources of *E. coli* bacteria and the attainment of the water quality standards for *E. coli* bacteria.
- Describe the approach that will be taken to develop, test, and evaluate various alternatives for meeting the water quality standards. The alternatives will address the distribution of the loading capacity among wasteload allocations (WLAs), load allocations (LAs), and natural background.
- Describe the approach that will be taken to address a margin of safety and seasonal variations, as required by Section 303(d)(1)(C) of the Clean Water Act.



**Figure 1. Political map of the Lake Michigan watershed in Indiana.**

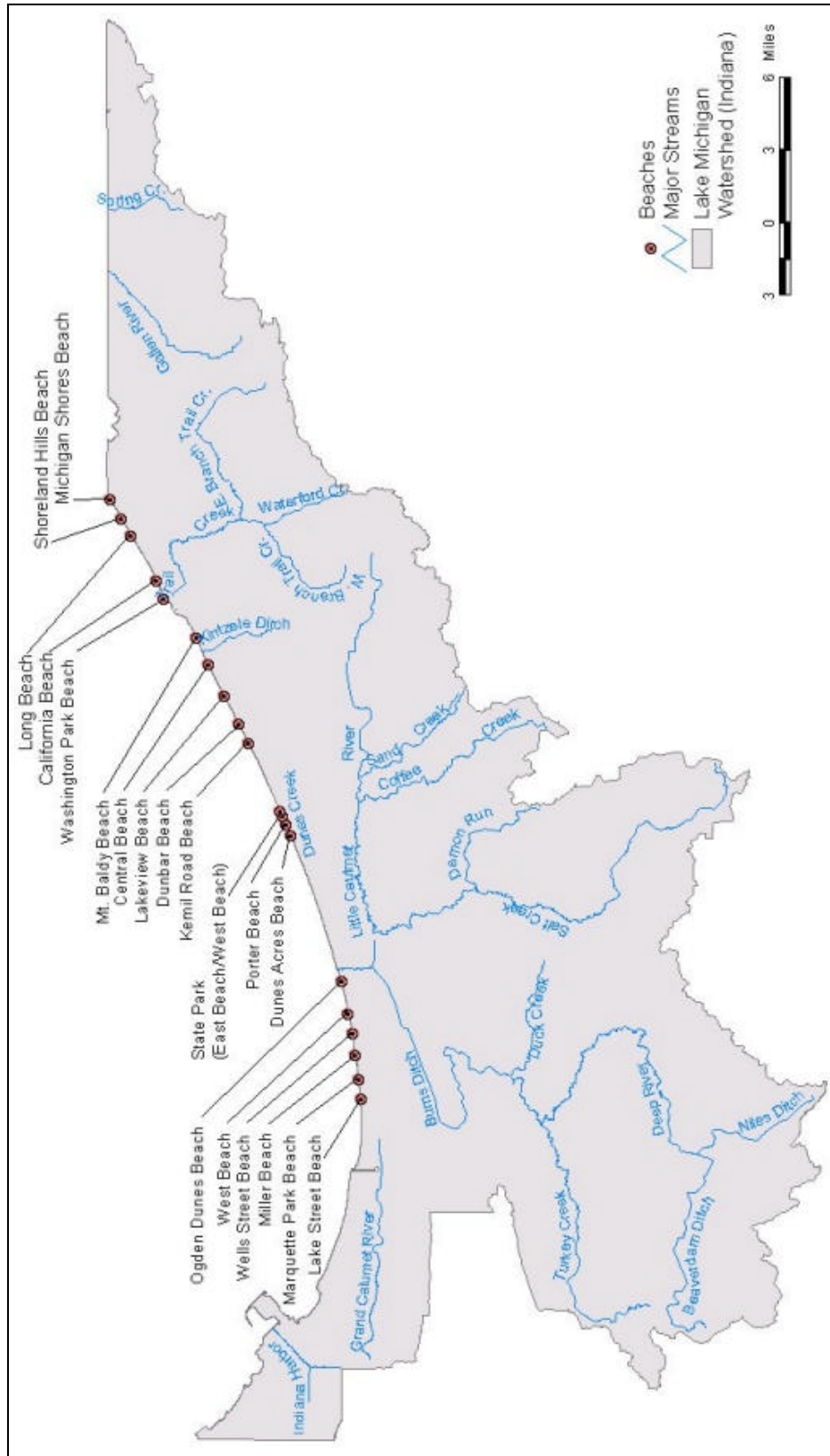


Figure 2. Tributaries and beaches in Lake Michigan shoreline study area.

## 2.0 MODEL SELECTION

To meet the objectives defined for the Lake Michigan Shoreline TMDL, we believe that development of a comprehensive 2-dimensional hydrodynamic transport model is necessary to represent the study area. Hydrodynamic receiving water models are composed of a series of algorithms applied to characteristics data (i.e., bathymetry, meteorology, boundary elevations, etc.) to simulate flow and water quality of the waterbody. The characteristics data, however, represent physical and chemical aspects of a lake, river, or estuary. These models vary from simple 1-dimensional box models to complex 3-dimensional models capable of simulating water movement, salinity, temperature, sediment transport, and water quality.

### 2.1 Selection Criteria

In selecting an appropriate modeling platform to support management initiatives and development of TMDLs for the Lake Michigan Shoreline, the following criteria have been considered and addressed (expanding on classification of Mao, 1992):

- Technical Criteria
- Regulatory Criteria
- User Criteria

Technical criteria refer to the model's simulation of the physical system in question, including watershed and/or stream characteristics/processes and constituents of interest. Regulatory criteria make up the constraints imposed by regulations, such as water quality standards or procedural protocol. User criteria comprise the operational or economical constraints imposed by the end-user and include factors such as hardware/software compatibility and financial resources. The following discussion details considerations within each of these categories specific to the Lake Michigan Shoreline study area.

#### 2.1.1 Technical Criteria

Hydrodynamic and water quality modeling studies are based upon four principles: (1) conservation of momentum, (2) conservation of mass and energy, (3) thermodynamics, and (4) ecological interactions and processes.

An environmental modeling framework for pathogens such as *E. coli* bacteria is designed to represent the most important physical transport processes, pollutant loads, and physical, chemical, and biological processes representing the fate of the pathogens while maintaining mass balance. This type of modeling study is designed to describe how releases of pathogens are transported and become distributed along the lakeshore. The key components of an environmental modeling framework are quantitative descriptions of (a) the inputs of the pathogens; (b) water motion from physical transport; and (c) kinetic reactions that impact the fate of the pathogens.

Pathogen loading from streams entering Lake Michigan will be quantified by the ongoing TMDLs being developed for the Little Calumet River/Burns Ditch, Salt Creek, and Trail Creek. Other pathogen sources that will need to be quantified for the lakeshore model include wildlife, waterfowl, and failing septic systems. Therefore the following considerations are critical to modeling the Lake Michigan shoreline area.

- The model must be able to incorporate the pathogen loads from the various sources including stream loads, wildlife and waterfowl loads, and diffuse loads from leaking septic systems.
- Rainfall intensity and volume play an important role in pathogen loadings. The model must provide adequate time-step estimation of flow and not over-simplify storm events.

- Different sources influence receiving waters in different ways and at different times (through different transport mechanisms). For example, surface runoff from streams impacts the lakeshore most significantly during storm events whereas wildlife can impact the lakeshore waters during any time period. The model must be capable of incorporating these different loading mechanisms.
- The model should represent the horizontal transport and dispersion of pathogens due to hydraulic and wind induced mechanisms as well as diffusive mechanisms in the 2-dimensional horizontal domain.
- Representation of the potential decay of the pathogen due to natural processes (dependent on sunlight and temperature) should be addressed in the model.

### 2.1.2 Regulatory Criteria

A properly designed and applied model provides the source-response linkage component of the TMDL and enables accurate assimilative capacity assessment and allocation proposition. A waterbody's assimilative capacity is determined through adherence to predefined water quality criteria. IDEM's surface water quality standards for the designated uses of the Lake Michigan Shoreline are as follows:

“This subsection establishes bacteriological quality for recreational uses. In addition to subsection (a), the criteria in this subsection are to be used to evaluate waters for full body contact recreational uses, to establish wastewater treatment requirements, and to establish effluent limits during the recreational season, which is defined as the months of April through October, inclusive. *E. coli* bacteria, using membrane filter (MF) count, shall not exceed one hundred twenty-five (125) per one hundred (100) milliliters as a geometric mean based on not less than five (5) samples equally spaced over a thirty (30) day period nor exceed two hundred thirty-five (235) per one hundred (100) milliliters in any one (1) sample in a thirty (30) day period.” [Source: Indiana Administrative Code Title 327 Water Pollution Control Board. Last Updated October 1, 2002]

In selecting the modeling system, consideration was given to the regulatory targets designated by IDEM for TMDL development. The selected model must be capable of simulating these water quality parameters using time-series simulation so that applicable averaging periods and peak levels can be determined and compared to numeric targets. The selected model must also be able to address seasonal variations in hydrology and water quality as well as critical conditions (i.e., periods when *E. coli* concentrations are at their highest) as required by TMDL regulations.

### 2.1.3 User Criteria

User criteria are determined by the needs, expectations, and resources of IDEM and the stakeholders in the Lake Michigan shoreline study area. Although no modeling preferences have as yet been expressed by residents of the study area, it is clear that they want to use the best approach possible. This is due to their desire to have waters that meet water quality standards in addition to the possibility that they might be asked to commit financial and other resources to reduce loads of *E. coli*. They want to know that efforts are being focused on the appropriate sources and the best science has been used to estimate the magnitude of necessary load reductions.

Furthermore, modeling software must be compatible with existing personal-computer-based hardware platforms. The modeling software should be well-documented, tested, and accepted since it may be used for future planning and permitting decisions. Because IDEM is a public agency the software should also be publicly available and not proprietary. Another consideration is that future impairments might be

identified in the Lake Michigan Shoreline study area. Therefore another factor to consider is whether the chosen model can address these impairments.

From a resource perspective, the level of effort required to develop, calibrate, and apply the model must be commensurate with available funding, without compromising the ability to meet technical criteria. In addition to these primary criteria, the required time-frame for model development, application, and completion is important.

## **2.2 Review of Available Models/Approaches**

The models described in this section have been identified as potentially being appropriate for development of the Lake Michigan Shoreline *E. coli* TMDL.

### **2.2.1 CORMIX**

The Cornell Mixing Zone Expert System (CORMIX) predicts plume geometry and dilution characteristics within a receiving water's initial mixing zone and allows an analysis of toxic or conventional pollutant discharges into ambient waterbodies. The model is able to consider nonconservative pollutants with first-order decay and wind effects on thermal plume mixing. Three submodels within the CORMIX system can be applied to predict the geometry and dilution characteristics of effluent flow from different discharging systems. The first submodel, CORMIX1 (Doneker and Jirka, 1990), considers a submerged single-port diffuser of arbitrary density discharging into a water body that may have ambient stratification. The second submodel, CORMIX2 (Akar and Jirka, 1991) applies to commonly used types of submerged multiport diffuser discharges under the same general effluent and ambient conditions as CORMIX1. The third submodel, CORMIX3 (Jones and Jirka, 1991), considers buoyant surface discharges that result when an effluent enters a larger waterbody laterally through a canal, channel, or near-surface pipe.

There are two major weaknesses to the CORMIX approach. First, it assumes steady-state ambient and discharge conditions. Therefore, it would not be possible to simulate the transient nature of pathogen loadings from the streams during a storm event. Second, CORMIX would not be able to accommodate pathogen loading from wildlife and waterfowl or from diffuse sources such as leaking septic systems.

### **2.2.2 Water Quality Analysis Simulation Program (WASP)**

WASP (Ambrose et al., 1993) is a generalized framework for modeling water quality and contaminant fate and transport in surface waters. Based on the flexible compartment modeling approach, WASP can be applied in one, two, or three dimensions. WASP is designed to permit easy substitution of user-written routines into the program structure. Problems that have been studied using the WASP framework include biochemical oxygen demand and dissolved oxygen dynamics, nutrients and eutrophication, bacterial contamination, and organic chemical and heavy metal contamination.

The most recent version of WASP is WASP 6.1, which has been redeveloped in the Microsoft Windows (95/98/Me/NT/2000) environment to provide a graphical user interface for the development of input files. An advanced graphical post processor allows scientists and engineers to rapidly evaluate the model results. The user can plot field data versus predicted model results. Included in version 6.1 are the Thermal and Pathogen models. The Thermal and Pathogen model allows the user to simulate temperature using one of two approaches (full heat balance or equilibrium heat balance) as well as model the fate and transport of pathogens such as *E. coli*.



WASP is an advanced model and requires extensive input parameters. WASP provides the ability to evaluate pathogen concentrations at a fine spatial and temporal resolution. For complex 2-D and 3-D applications, it is necessary to link WASP to a hydrodynamic model, such as EFDC, in order to provide the proper flow transport mechanisms.

### 2.2.3 CE-QUAL-ICM

CE-QUAL-ICM (Cерco and Cole, 1993) incorporates detailed algorithms for water quality kinetics. Interactions among state variables are described in 80 partial-differential equations that employ over 140 parameters. The model may be applied to most waterbodies in 1-, 2-, or 3-dimensions. For complex 2-D and 3-D applications, it is necessary to link CE-QUAL-ICM to a hydrodynamic model, such as CH3D-WES (Johnson et al., 1993) or EFDC, in order to provide the proper flow transport mechanisms.

A major weakness of the CE-QUAL-ICM model is that it does not simulate pathogens directly. Instead, one of the water quality variables (e.g., ammonia nitrogen) can be selected as a surrogate variable with all other water quality variables and kinetics turned off. The pathogen decay can be approximated through the use of the ammonia nitrification rate constant.

### 2.2.4 Environmental Fluid Dynamics Code (EFDC)

The EFDC model (Hamrick, 1992) solves the vertically hydrostatic, free-surface, variable-density turbulent-averaged equations of motion and transport equations for turbulence intensity and length scale, salinity, and temperature in a stretched, vertical coordinate system, and either a Cartesian or curvilinear-orthogonal horizontal coordinate system. Equations describing the transport of suspended sediment, toxic contaminants, water quality state variables, and pathogens may also be solved by EFDC. Also simulated are multiple size classes of cohesive and non-cohesive sediments and associated deposition and resuspension processes as well as bed geomechanics. Toxics are transported in both the water and sediment phases in the water column and bed. The built-in 22 state-variable water quality model is based on the reaction kinetics of CE-QUAL-ICM. Other model features include wetting and drying of grid cells, representation of hydraulic structures, vegetation resistance, and Lagrangian particle tracking. The model also accepts radiation stress fields from wave refraction-diffraction models allowing simulation of alongshore currents and sediment transport.

Input data to drive the EFDC model include open boundary water surface elevations, wind speed and direction, atmospheric thermodynamic conditions, open boundary salinity and temperature, volumetric inflows, and inflowing concentrations of sediment and water quality variables. Model outputs include water surface elevation, horizontal velocities, salinity, temperature, sediment concentration, pathogen concentration, and toxicant concentration. Water quality concentrations can be output in a variety of formats suitable for time-series analysis and plotting, horizontal and vertical contour plotting, and three-dimensional slice and volumetric visualization.

### 2.2.5 Evaluation Summary

The various technical, regulatory, and user criteria for each of the four models considered are summarized in Table 1. The CORMIX model is not considered appropriate due to its steady-state characteristics and lack of far-field fate and transport capabilities. The WASP and CE-QUAL-ICM models could be used for the project, however, they require linking to a 2-D or 3-D hydrodynamic model to provide the necessary advective transport. The EFDC hydrodynamic and water quality model is proposed for the Lake Michigan Shoreline study because it best matches the required criteria in Table 1.

**Table 2. Evaluation of models for developing Lake Michigan Shoreline *E. coli* TMDLs.**

Criteria	CORMIX	WASP	CE-QUAL-ICM	EFDC
<b>Technical Criteria</b>				
Simulate stream flow loads	~	▲	▲	▲
Simulate wildlife and waterfowl loads	▽	▲	▲	▲
Simulate diffuse loading from leaking septs, etc.	▽	▲	▲	▲
Simulate storm events (dynamic time step)	▽	▲	▲	▲
Includes pathogen decay kinetics	▲	▲	~	▲
Includes 2-D and 3-D hydrodynamics	▽	▽	▽	▲
Includes pathogens ( <i>E. coli</i> ) as a state variable	~	▲	~	▲
<b>Regulatory Criteria</b>				
Output can be directly compared to WQS	▽	~	~	~
Simulates seasonal differences in hydrology and loads	▽	▲	▲	▲
Provides output for critical conditions	~	▲	▲	▲
<b>User Criteria</b>				
Provides detailed information on sources	▽	~	~	▲
Can address other pollutants	▽	▲	▲	▲
Publicly available	▽	▲	~	▲

▲ Model addresses criteria

~ Model only partially addresses criteria

▽ Model does not address criteria

### 3.0 PROPOSED MODELING APPROACH

Development and application of the water quality model to address the project objectives will involve several important steps:

1. Development of computational grid for the waterbody
2. Configuration of key model components
3. Model calibration and validation
4. Model simulation for existing conditions and scenarios
5. Determine margin of safety

#### 3.1 Computational Grid

The waters adjacent to the Lake Michigan shoreline will be segmented into a computational grid for the EFDC model. The grid will extend from the Michigan-Indiana state line on the east to the Illinois-Indiana state line on the west, a distance of about 43 miles. The grid will also extend offshore a distance of about 2,000 meters from the Indiana shoreline. The size of an individual grid cell will be approximately 100 meters horizontally. The entire grid network will consist of about 12,000 grid cells. The grid-cell size was based on several factors including spatial resolution, model run time, and size of the study area. Based on the availability of calibration data, the size of the study area, and the scope of the project, an initial grid network has been developed as shown in Figure 3.

#### 3.2 Configuration of Key Model Components

Configuration of the model itself will involve consideration of four major components: waterbody representation, meteorological data, and hydrologic and pollutant loading representation. These components provide the basis for the model's ability to estimate the fate and transport of pollutant loadings. Meteorological data essentially drive the hydrodynamic model. Wind speed and direction are key inputs to EFDC's transport algorithms. Hydrologic and pollutant representation refers to the EFDC modules or algorithms used to simulate hydrologic processes (e.g., surface runoff, pathogen loading from storm events and diffuse sources). Waterbody representation refers to the bathymetry used to determine water depths and surface elevations at model boundaries that determine general circulation patterns in the waterbody.

Meteorological data are a critical component of the model. Appropriate representation of precipitation, wind speed, wind direction, atmospheric pressure, cloud cover, temperature, and relative humidity are required to develop a valid model. These data provide necessary input to EFDC algorithms for hydrodynamic transport and water quality representation. Meteorological data have been accessed from a number of sources in an effort to develop the most representative dataset for the Lake Michigan shoreline study area. Hourly meteorological data are available from NOAA National Climatic Data Center (NCDC) weather stations located near the study area.

The hydrodynamic model of the near-shore waters will require bathymetric data. These data are available from the NOAA GeoDAS data base of hydrographic survey data. The GeoDAS data provide over 80,000 individual hydrographic soundings within the study area covered by the EFDC model. The hydrographic data will be used to determine the characteristic depth of each individual grid cell in the receiving water model.

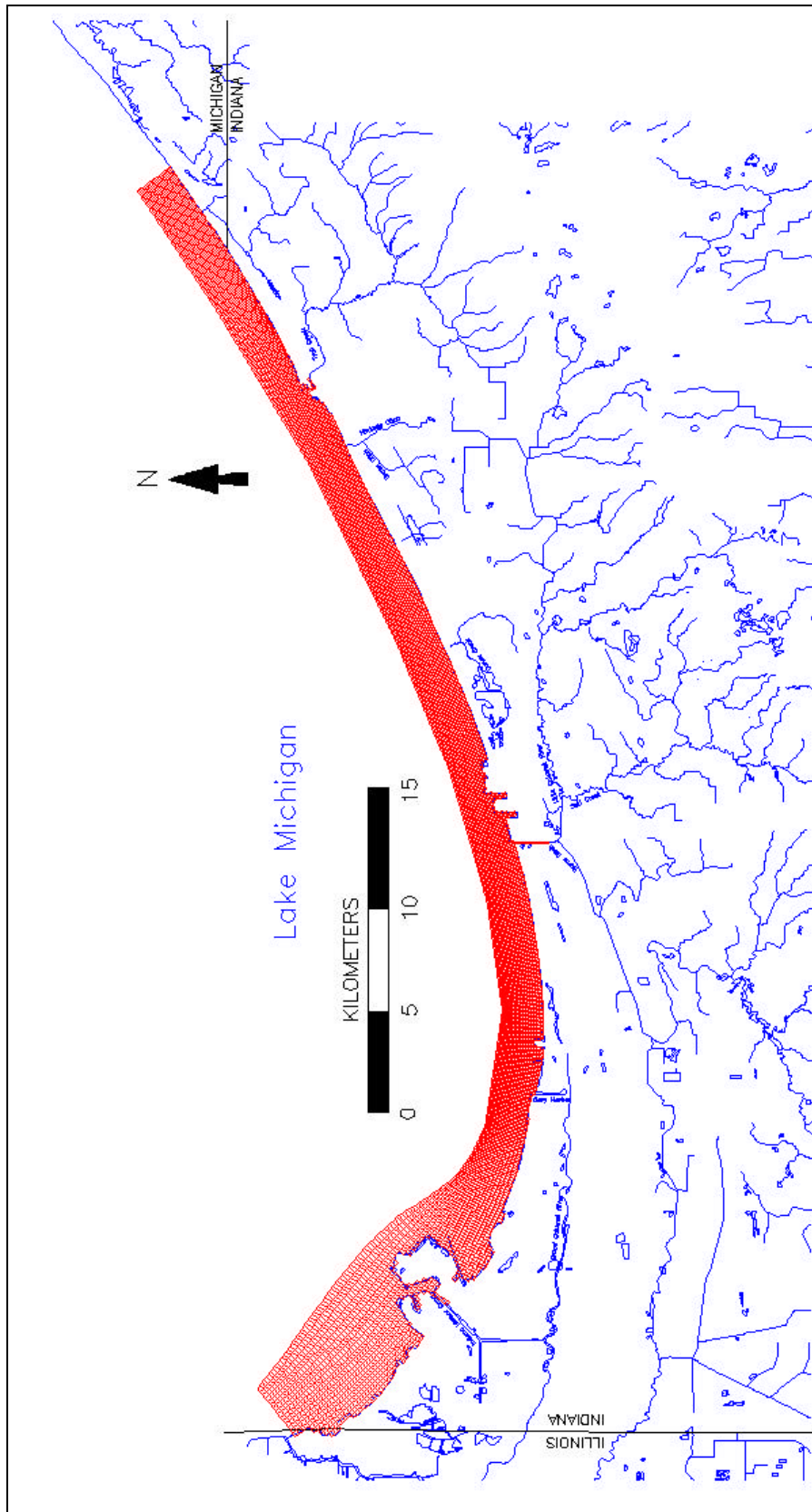


Figure 3. Model grid configuration for Lake Michigan Shoreline TMDL.

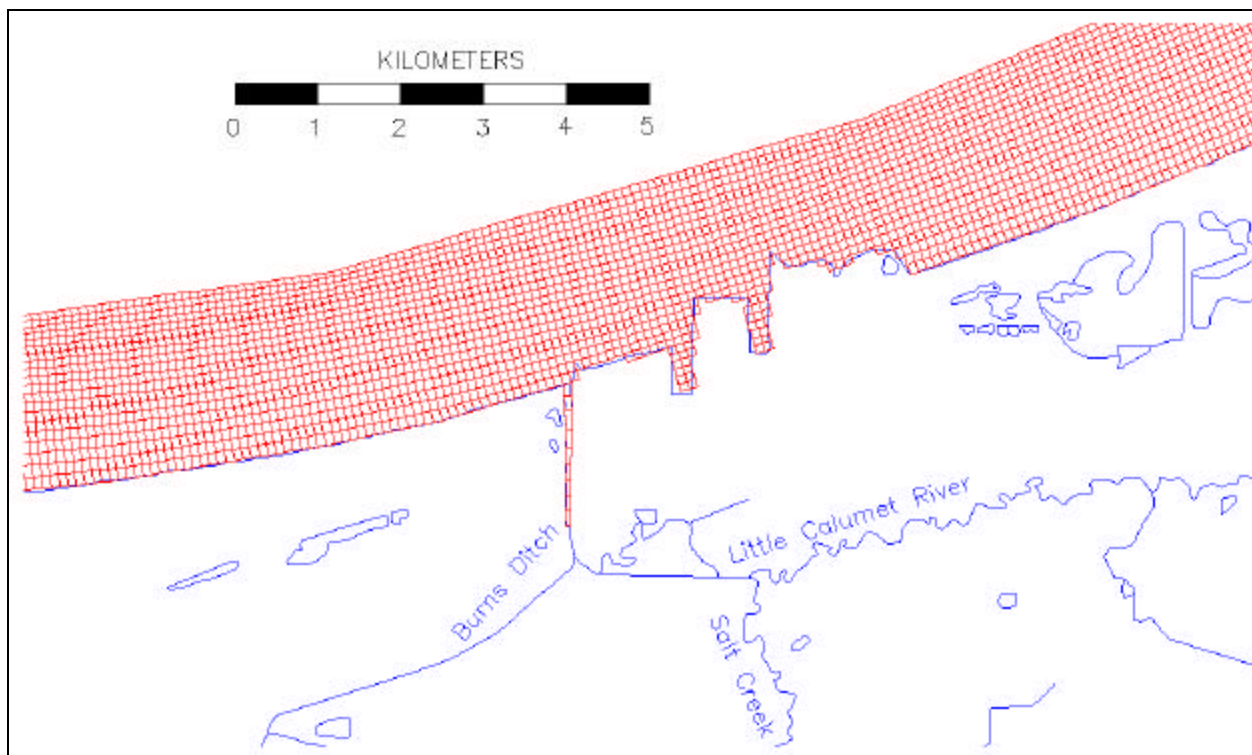


Figure 4. Grid configuration in vicinity of Burns Ditch.

Current flows in Lake Michigan have been studied for years, but many properties of seasonal circulation remain unreported because of the variable nature of lake currents. This variability requires costly long-term measurement programs to reliably estimate mean values. In contrast to the relatively stable ocean gyres, Lake Michigan currents lack persistence and depend more on short-term atmospheric forcing because of the relatively small size of the lake basin. Storm induced currents in Lake Michigan can be quite strong (up to 20 cm/sec or more), but the average currents are fairly weak throughout most seasons of the year averaging generally less than 4 cm/sec (Beletsky et al., 1999). Nevertheless, the mean circulation is important for this modeling study because it influences the transport pathway of the *E. Coli* pathogen contaminants. Lake current information for the modeling effort will be obtained from literature reports as well as from the NOAA data buoy (station 45007) located in southern Lake Michigan about 43 miles southeast of Milwaukee, Wisconsin.

### 3.3 Model Calibration and Validation

Model calibration and validation of the Lake Michigan shoreline EFDC hydrodynamic model will be performed after configuring the model using bathymetric, meteorologic, and loading data. Calibration refers to the adjustment or fine-tuning of model parameters to reproduce observations. If ample data are available, the model validation will be performed to test the calibrated parameters at different locations or for different time periods, without further adjustment. A calibrated input dataset containing parameter values will be developed for the study area upon completion of the calibration and validation efforts.

Calibration and validation will be completed by comparing the model time-series output to the available monitoring data. Output from the EFDC hydrodynamic model will be in the form of hourly average flow and velocity as well as hourly concentrations for the modeled pathogens at each grid cell in the study area. The velocities will be compared with information from literature reports and site-specific

measurements if available. Water quality monitoring data are available at a number of locations in the vicinity of beaches along the Lake Michigan shoreline.

The hydrodynamics will be the first model component calibrated, and it will involve a comparison of observed flow velocities to modeled velocities and an adjustment of key hydrodynamic parameters. The calibration time-period will be selected based upon an examination of available lake current velocity information. Key considerations in the hydrodynamic calibration will be the velocity speed and direction. Qualitative information such as the approximate size and shape of the discharge plume shown in an aerial photograph of Burns Ditch will also be used to validate the model. The model's accuracy will primarily be assessed through interpretation of the time-variable plots. The accuracy of the model predictions will also be assessed using statistical measures such as the relative error method. The relative error statistic is indicative of goodness of fit for the model-data calibration and validation efforts.

Water quality calibration will be performed following the hydrodynamic calibration and validation efforts. Modeled versus observed in-lake concentrations will be directly compared during model calibration and validation. The water quality calibration will consist of executing the watershed model, comparing water quality time series output to available water quality observation data, and adjusting pollutant loading and in-lake water quality parameters within a reasonable range. The objective will be to best simulate summertime conditions at water quality monitoring stations representative of different beaches in the lakeshore study area.

Water quality parameters for the receiving water model will be validated through a comparison of observed water quality data to modeled in-lake values. The validation will be performed, to the extent possible, at locations with sufficient water quality observation data located at beaches in the lakeshore study area.

### **3.4 Model Simulation for Existing Conditions and Scenarios**

The fully calibrated model will be run for an extended time period to generate hydrodynamic transport circulation and pathogen fate and transport under a variety of conditions. Model output will be summarized to provide insight into daily, monthly, and seasonal receiving water concentrations. The existing conditions represent the starting point for TMDL analyses. The allocation analysis is typically performed by following several discrete steps, as illustrated in Figure 5.

#### *Step 1: Application of the Model to Existing Conditions*

This application forms the current condition that is compared to available monitoring information for model testing and calibration.

#### *Step 2: Application of the Model to Existing Conditions with Point Sources at Permit Limits*

This application forms the baseline condition that will be reduced to meet the allowable load. The point sources are set at permit conditions using the permitted flow and mean daily concentration allowed for in the permit. If no permitted flow is available, the design flow or historic observed flow can be used.

#### *Step 3: Application of the Model to Future Conditions*

When future growth is considered, it can be added to the nonpoint and/or the point source loading contributions.

*Step 4: Develop and Test Allocation Scenarios*

Working from the baseline condition (Step 2, or Step 3 if future growth is considered), and considering the results of the source-response analysis, sample allocation scenarios are developed and applied. These scenarios are shown as A, B, and C in Figure 4. The results of each scenario are compared with the applicable water quality standard. The scenarios are adjusted until water quality standards (or loading capacity) are achieved.

*Step 5: Select Final TMDL Scenario*

The state selects the final TMDL scenario and results are processed to provide the required TMDL elements. Data processing is needed to provide the annual and monthly load for each category stipulated in the TMDL. The final scenario model input and output file is saved for the administrative record.

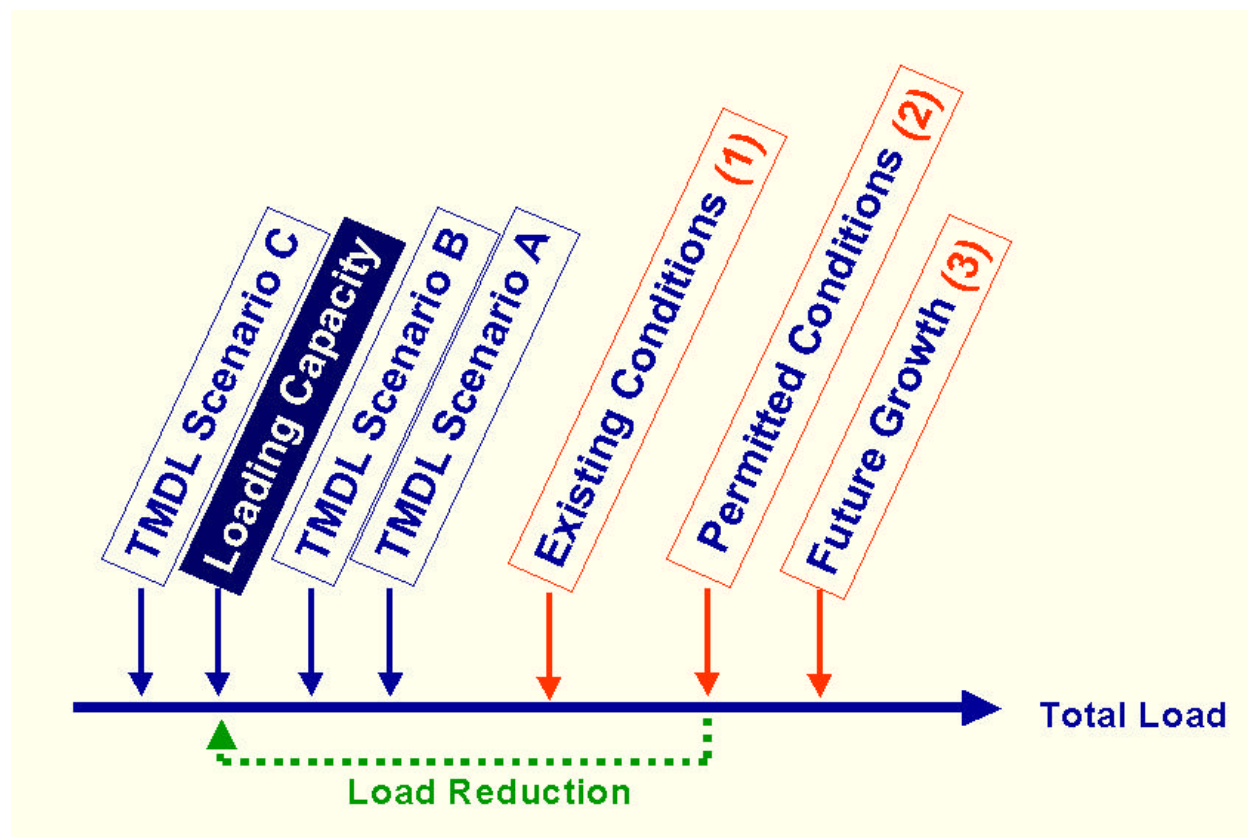


Figure 5. Steps in the TMDL allocation process.

### 3.5 Margin of Safety

Section 303(d) of the Clean Water Act and USEPA's regulations in 40 CFR 130.7 require that "TMDLs shall be established at levels necessary to attain and maintain the applicable narrative and numerical water quality standards with seasonal variations and a margin of safety which takes into account any lack of knowledge concerning the relationship between effluent limitations and water quality." The margin of safety can either be implicitly incorporated into conservative assumptions used to develop the TMDL or added as a separate explicit component of the TMDL (USEPA, 1991).

An explicit margin of safety will be incorporated into the Lake Michigan Shoreline TMDL by reducing the water quality target to provide additional assurance. The *E. coli* target will be set five percent lower than the numeric criteria in water quality standards.



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